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(54) **EYE-SAFE SCANNING LIDAR WITH VIRTUAL PROTECTIVE HOUSING**

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(52) **U.S. Cl.**

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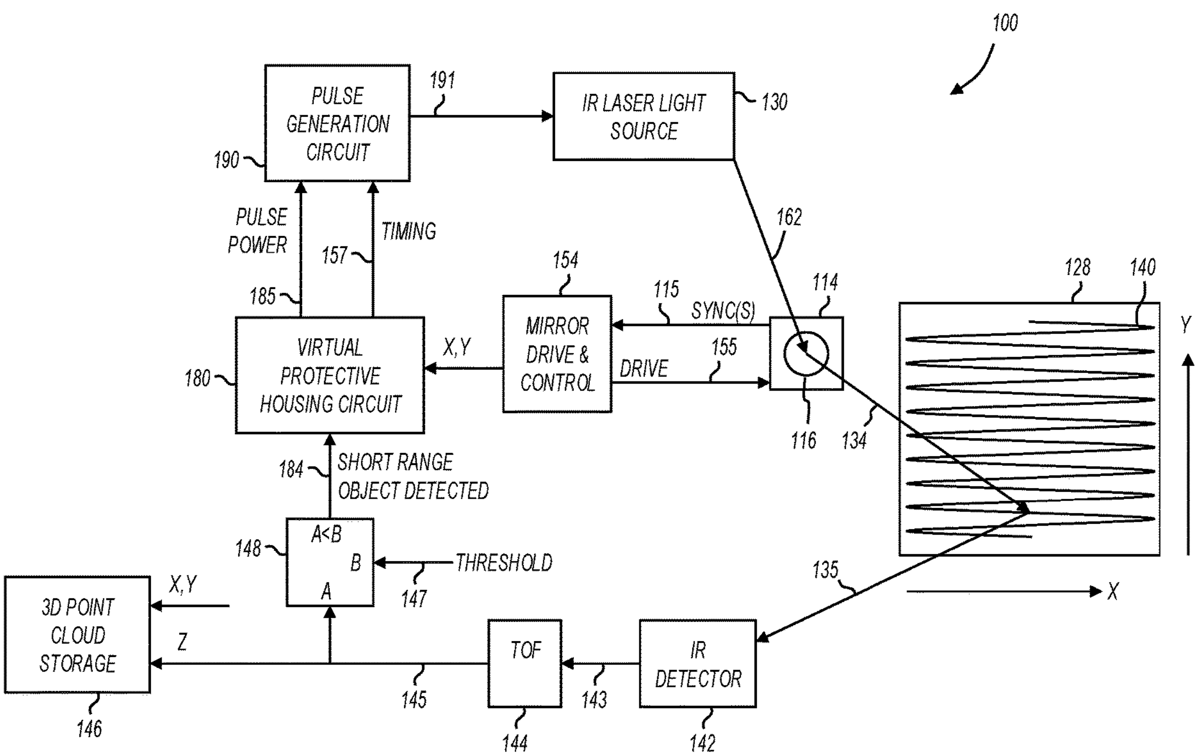
(57) **ABSTRACT**

An eye-safe light detection and ranging system includes a virtual protective housing. A short range pulse is emitted at every measurement point in a field of view before conditionally emitting a long range pulse. Short range pulses result in accessible emissions that are eye-safe at short distances and long range pulses result in accessible emissions that are eye-safe at longer distances.



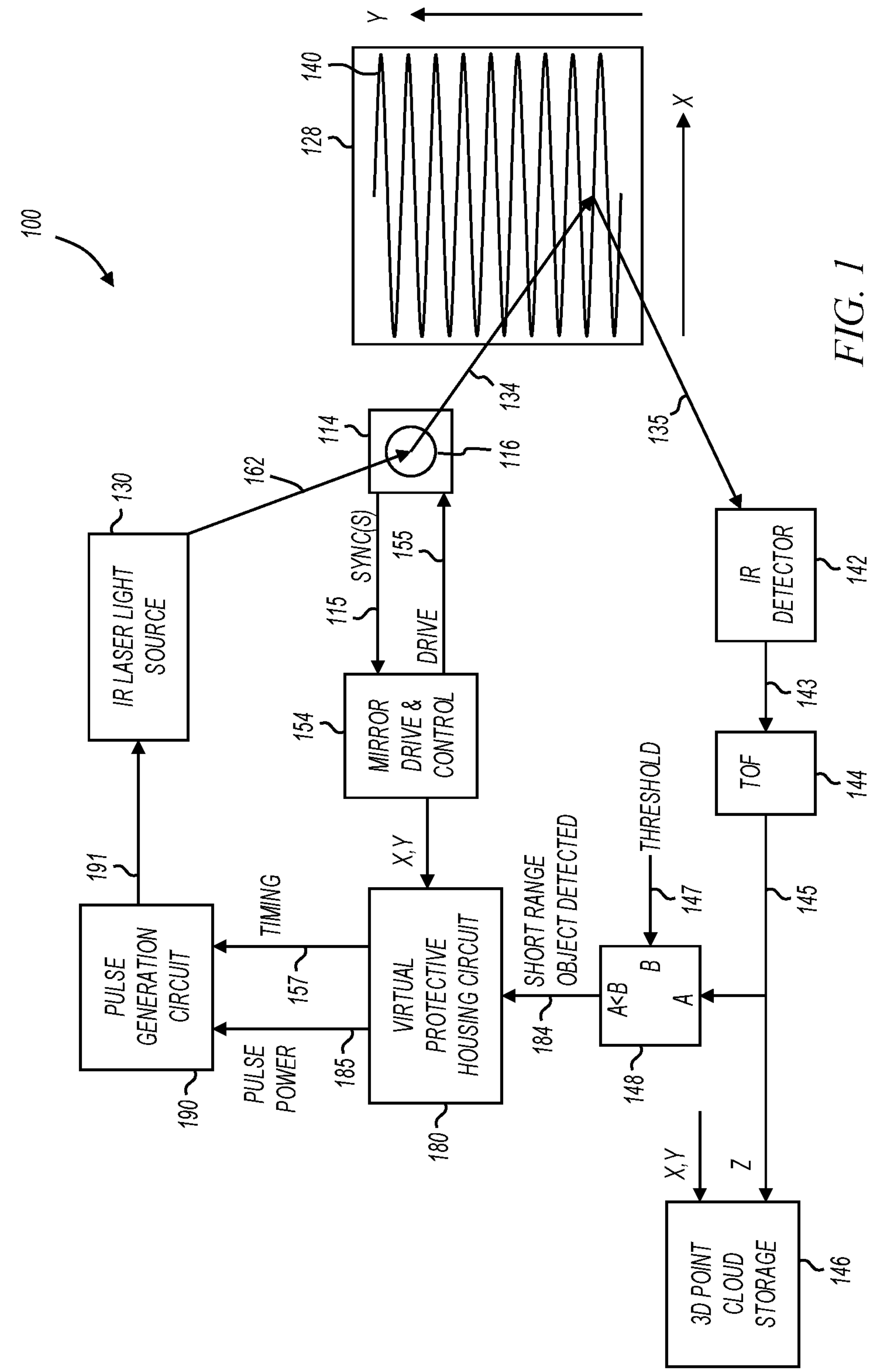

100
Y
X
140
128
114
116
134
135
162
130
IR LASER LIGHT SOURCE
SYNC(S)
115
155
DRIVE
MIRROR DRIVE & CONTROL
154
X,Y
IR DETECTOR
142
143
TOF
144
THRESHOLD
147
145
191
TIMING
157
VIRTUAL PROTECTIVE HOUSING CIRCUIT
SHORT RANGE OBJECT DETECTED
184
A<B
B
A
148
PULSE GENERATION CIRCUIT
190
PULSE POWER
185
180
X,Y
Z
3D POINT CLOUD STORAGE
146

FIG. 1

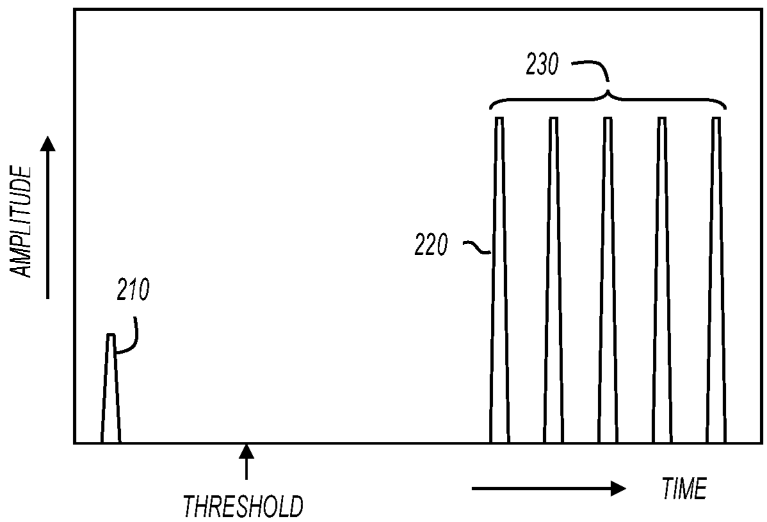


FIG. 2

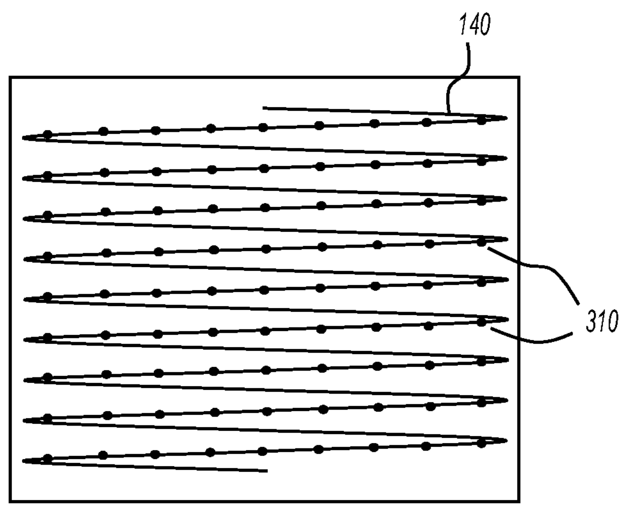


FIG. 3

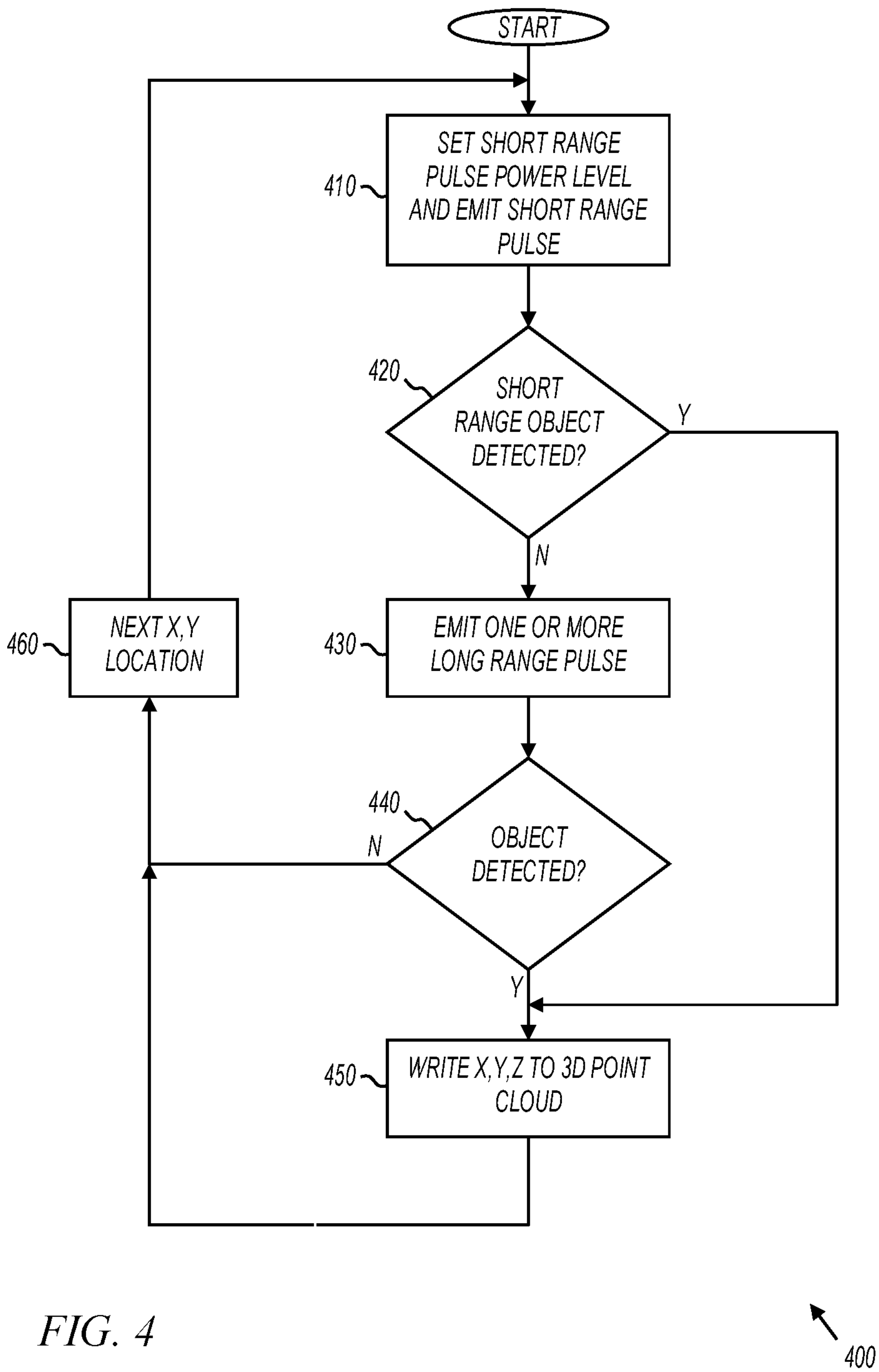

START
SET SHORT RANGE PULSE POWER LEVEL AND EMIT SHORT RANGE PULSE
410
SHORT RANGE OBJECT DETECTED?
420
Y
N
EMIT ONE OR MORE LONG RANGE PULSE
430
NEXT X,Y LOCATION
460
OBJECT DETECTED?
440
N
Y
WRITE X,Y,Z TO 3D POINT CLOUD
450
400

FIG. 4

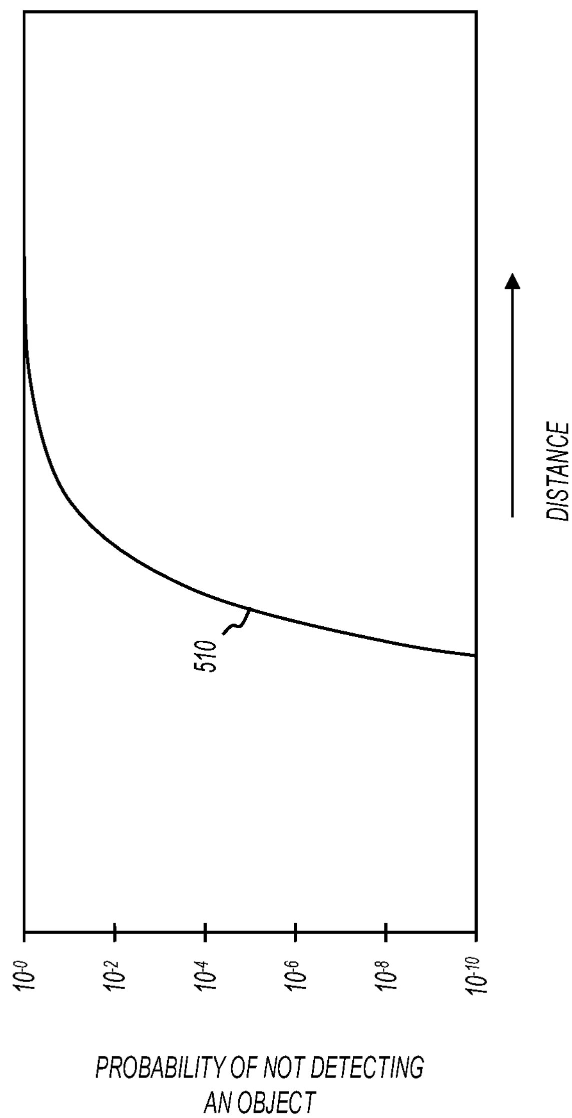

PROBABILITY OF NOT DETECTING AN OBJECT
10-0
10-2
10-4
10-6
10-8
10-10
DISTANCE
510

FIG. 5

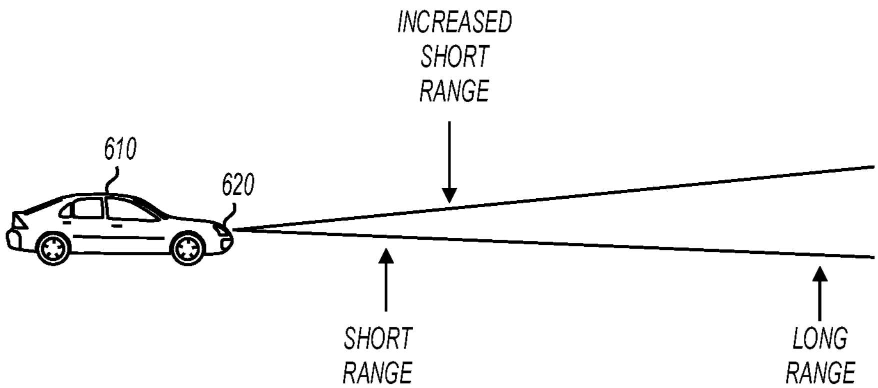

INCREASED
SHORT
RANGE
610
620
SHORT
RANGE
LONG
RANGE

FIG. 6

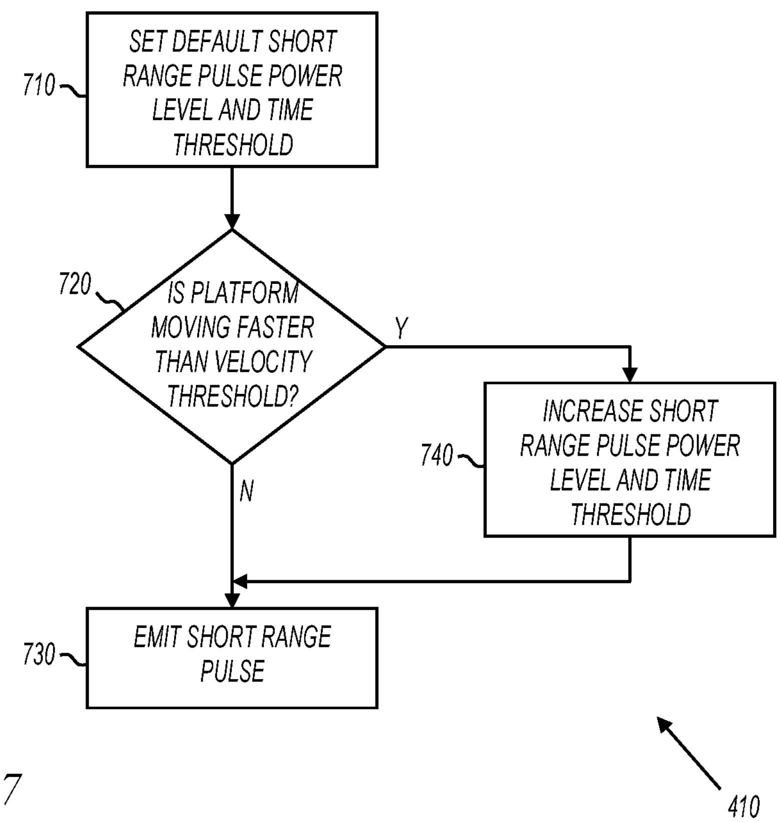

710
SET DEFAULT SHORT RANGE PULSE POWER LEVEL AND TIME THRESHOLD
720
IS PLATFORM MOVING FASTER THAN VELOCITY THRESHOLD?
Y
N
740
INCREASE SHORT RANGE PULSE POWER LEVEL AND TIME THRESHOLD
730
EMIT SHORT RANGE PULSE
410

FIG. 7

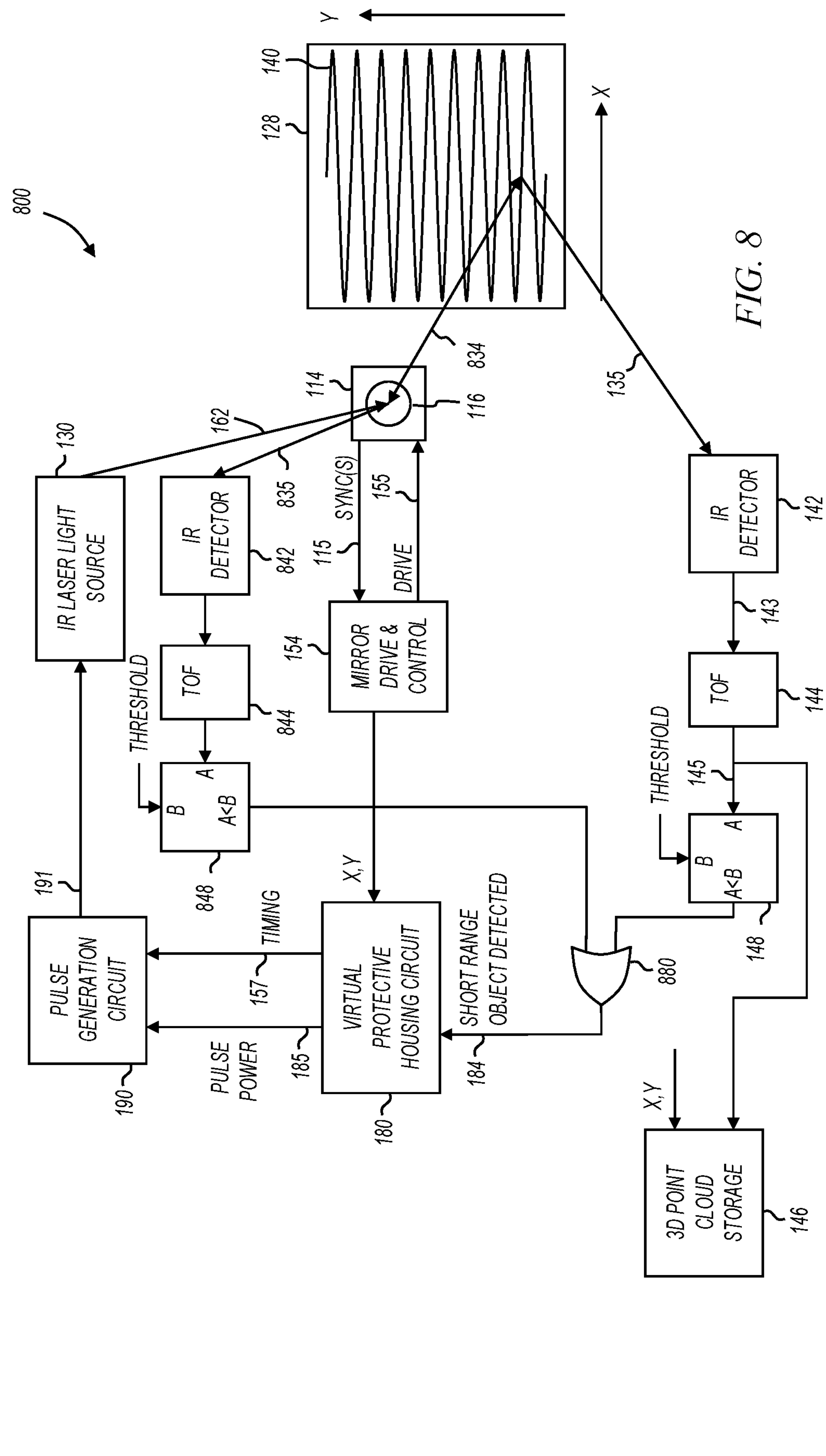

800
Y
X
140
128
114
116
834
162
135
130
IR LASER LIGHT SOURCE
IR DETECTOR
842
835
SYNC(S)
115
155
DRIVE
MIRROR DRIVE & CONTROL
154
TOF
844
THRESHOLD
B
A
A<B
848
IR DETECTOR
142
143
TOF
144
THRESHOLD
145
B
A
A<B
148
880
191
PULSE GENERATION CIRCUIT
190
TIMING
157
PULSE POWER
185
X,Y
VIRTUAL PROTECTIVE HOUSING CIRCUIT
180
SHORT RANGE OBJECT DETECTED
184
X,Y
3D POINT CLOUD STORAGE
146

FIG. 8

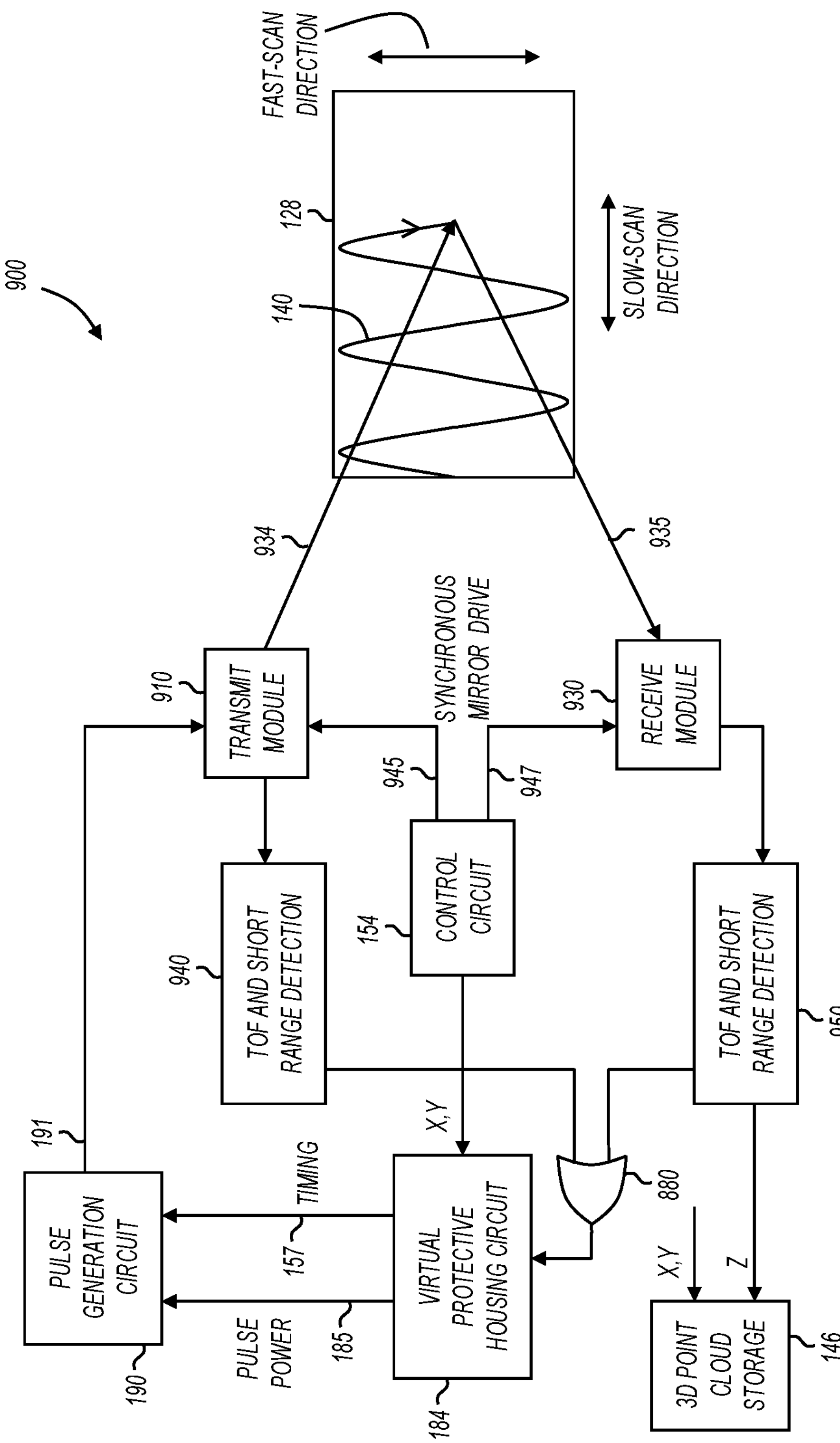
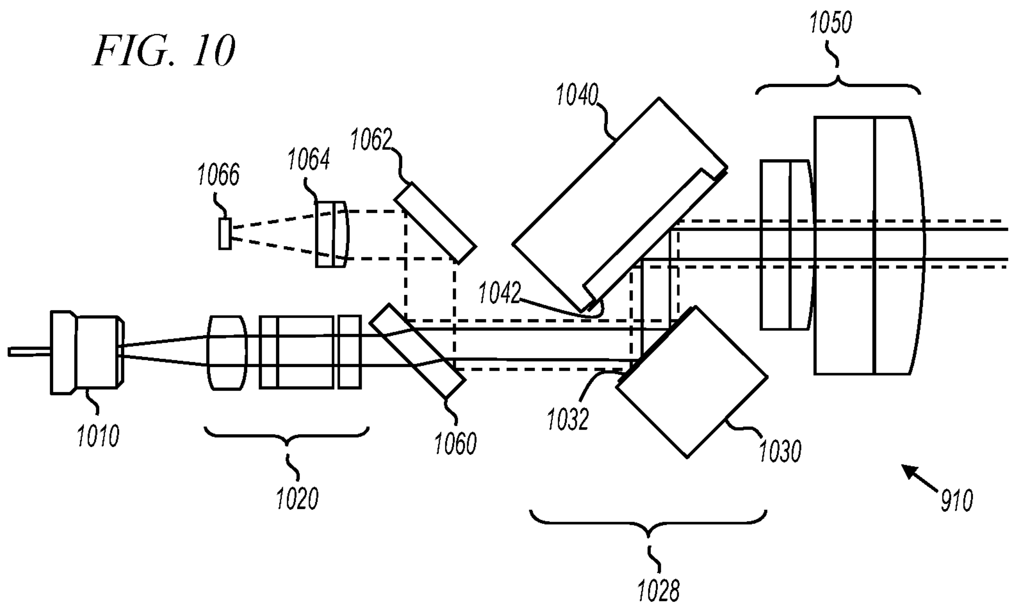

900
FAST-SCAN DIRECTION
128
140
SLOW-SCAN DIRECTION
934
935
SYNCHRONOUS MIRROR DRIVE
910
TRANSMIT MODULE
930
RECEIVE MODULE
945
947
CONTROL CIRCUIT
154
940
TOF AND SHORT RANGE DETECTION
950
TOF AND SHORT RANGE DETECTION
X,Y
880
191
PULSE GENERATION CIRCUIT
190
TIMING
157
PULSE POWER
185
VIRTUAL PROTECTIVE HOUSING CIRCUIT
184
X,Y
Z
3D POINT CLOUD STORAGE
146

FIG. 9

FIG. 10


1050
1040
1062
1064
1066
1042
1010
1020
1060
1032
1030
1028
910

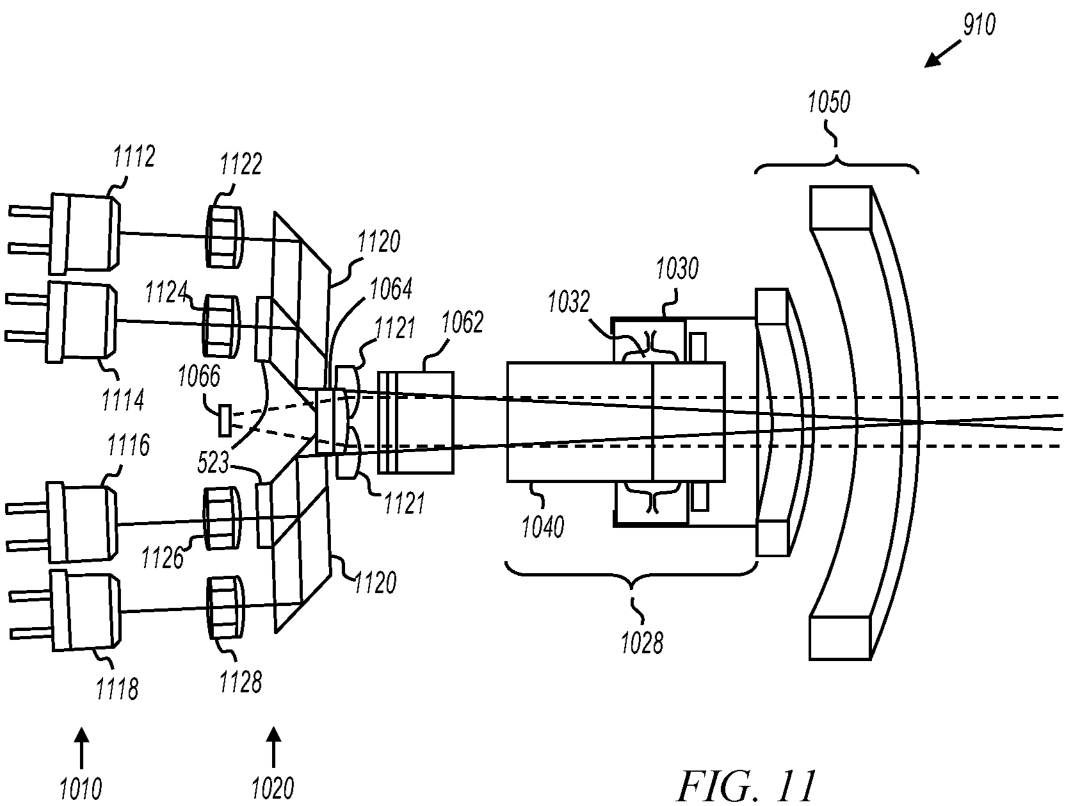

910
1050
1112
1122
1120
1064
1124
1121
1062
1030
1032
1066
523
1116
1121
1040
1126
1120
1028
1118
1128
1010
1020

FIG. 11

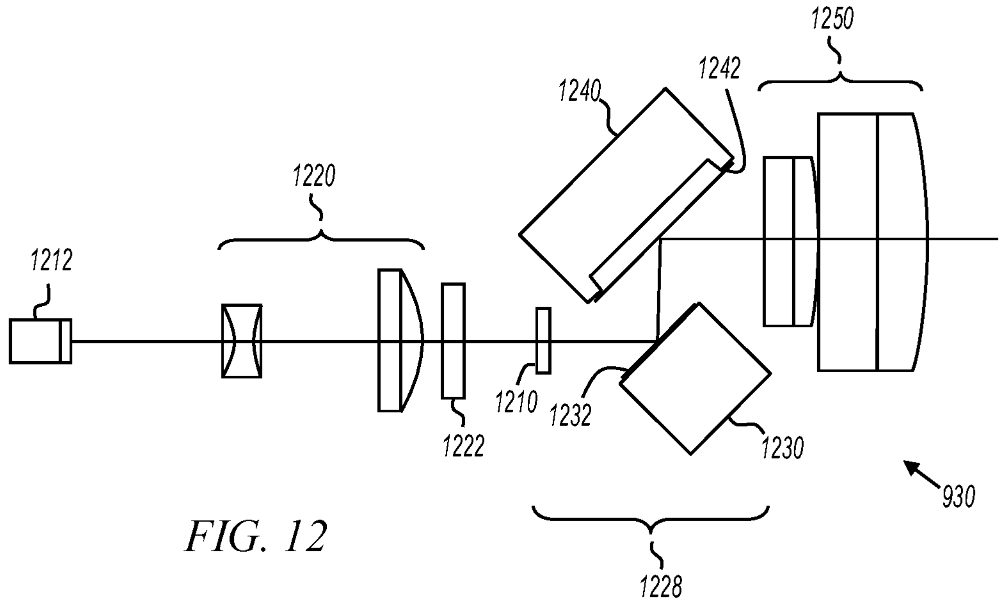

1250
1242
1240
1220
1212
1210
1232
1222
1230
930
1228

FIG. 12

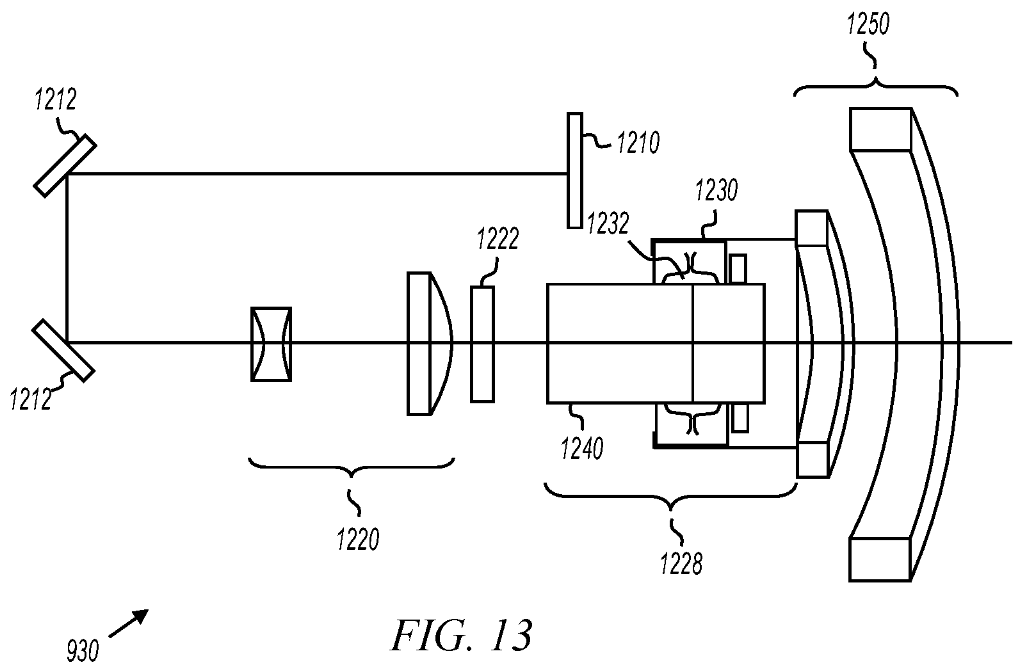

1250
1212
1210
1230
1232
1222
1212
1240
1220
1228
930

FIG. 13

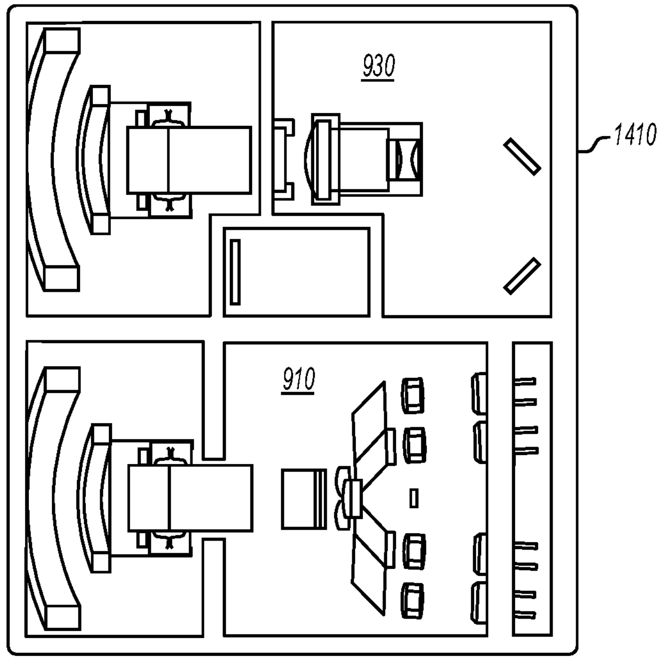


FIG. 14

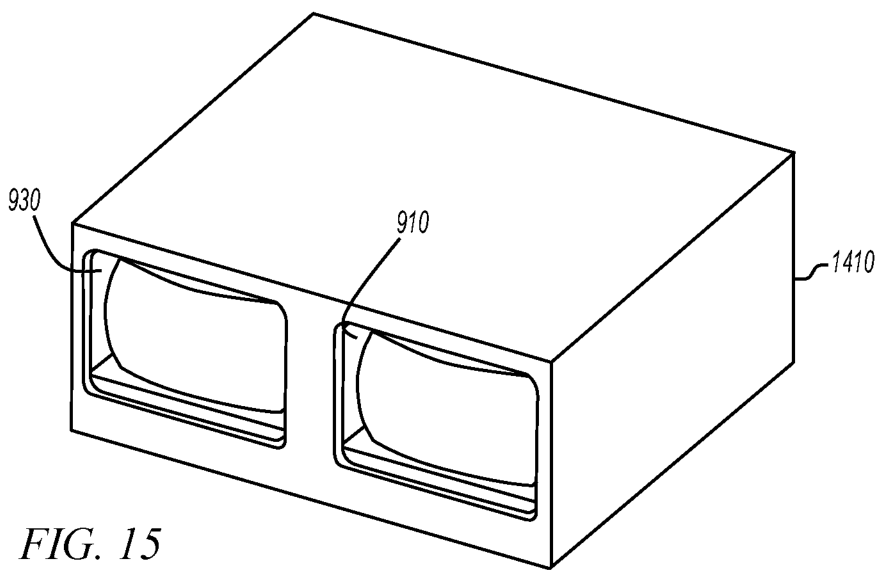


FIG. 15

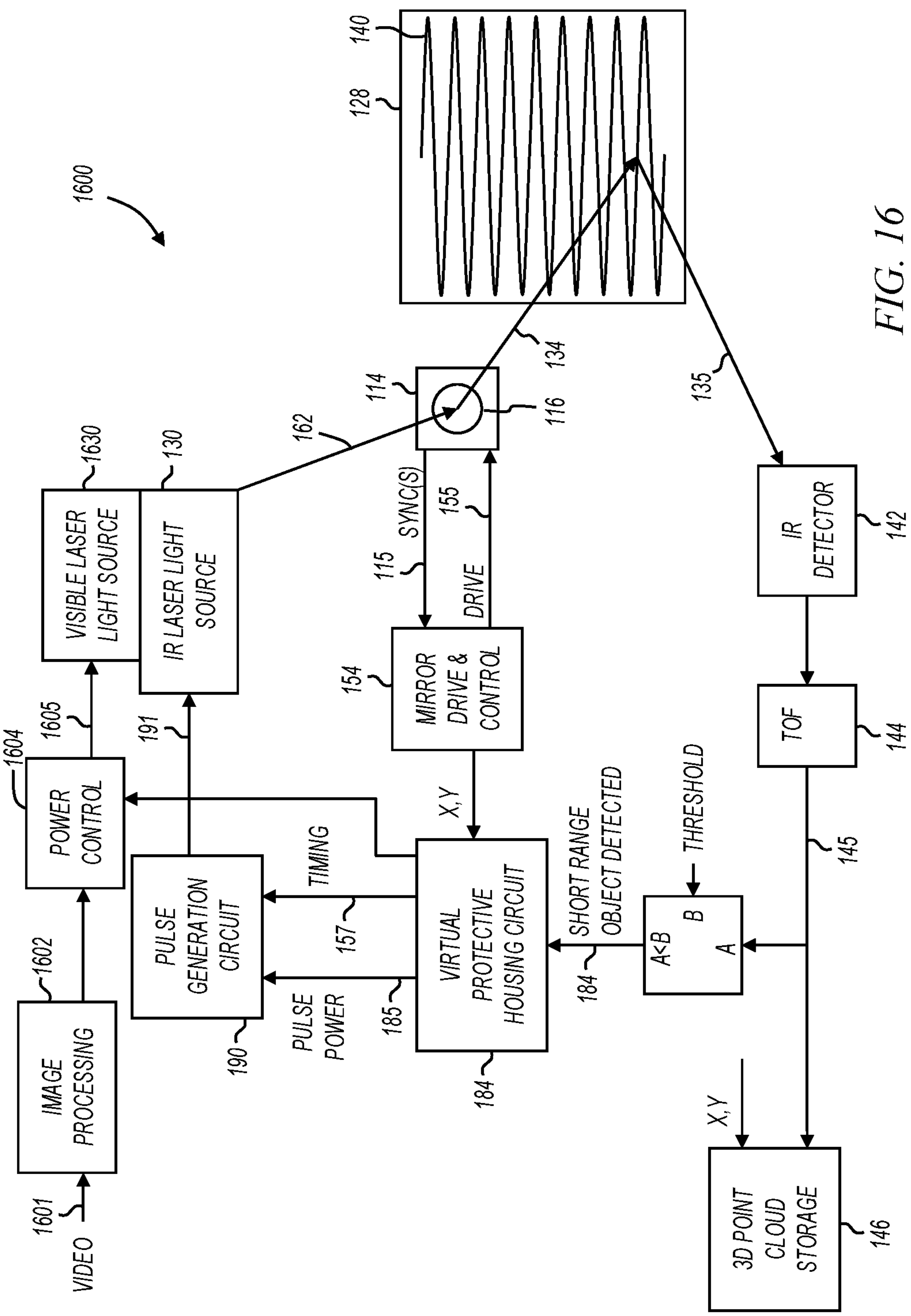

1600
VIDEO
1601
IMAGE PROCESSING
1602
POWER CONTROL
1604
1605
VISIBLE LASER LIGHT SOURCE
1630
IR LASER LIGHT SOURCE
130
191
PULSE GENERATION CIRCUIT
190
TIMING
157
PULSE POWER
185
162
114
116
SYNC(S)
115
155
DRIVE
MIRROR DRIVE & CONTROL
154
X,Y
VIRTUAL PROTECTIVE HOUSING CIRCUIT
184
SHORT RANGE OBJECT DETECTED
184
A<B
B
A
THRESHOLD
134
140
128
135
IR DETECTOR
142
TOF
144
145
X,Y
3D POINT CLOUD STORAGE
146

FIG. 16

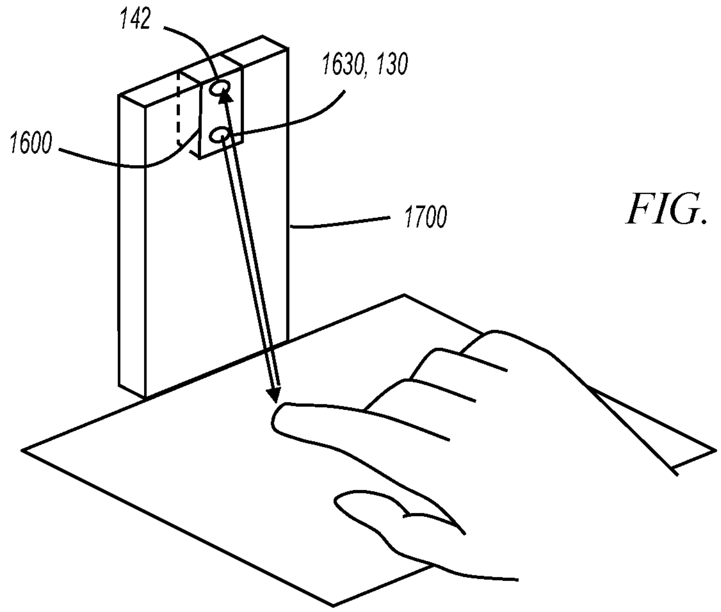


FIG. 17

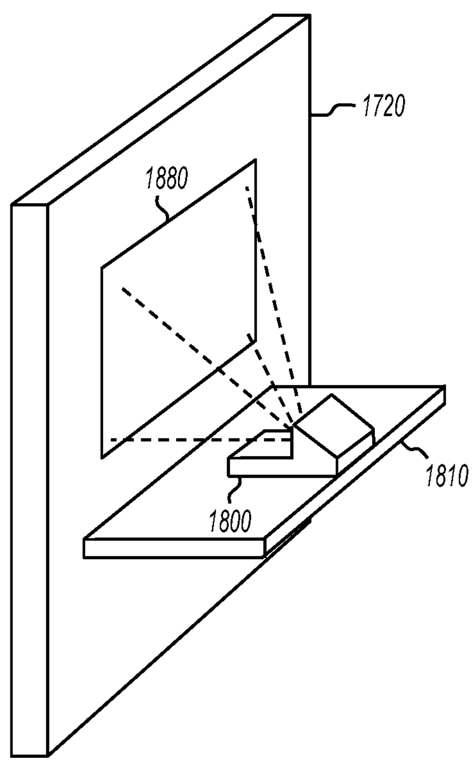


FIG. 18

EYE-SAFE SCANNING LIDAR WITH VIRTUAL PROTECTIVE HOUSING

FIELD

[0001] The present invention relates generally to light detection and ranging (LIDAR) systems, and more specifically to safety of LIDAR systems.

BACKGROUND

[0002] Products that include laser devices generally fall into different laser safety classes based on the possibility that they can cause damage to the human eye or skin. International Standard IEC 60825.1 describes example laser safety classes. Although many different laser safety classes exist, one major distinction between classes is whether a product is considered "eye-safe" or "non-eye-safe." Eye-safe laser systems are generally considered to be incapable of producing damaging accessible radiation levels during operation, and are also generally exempt from device marking requirements, control measures, or other additional safety measures. IEC 60825.1 classifies eye-safe products as Class 1. Products that include high power laser devices that would otherwise be classified as non-eye-safe, may nevertheless be classified as eye-safe if the product includes additional safety measures such as a protective housing that reduces the accessible emission limits to a safe level.

BRIEF DESCRIPTION OF THE DRAWINGS

[0003] FIG. **1** shows a scanning light detection and ranging (LIDAR) system with a virtual protective housing in accordance with various embodiments of the present invention;

[0004] FIG. **2** shows short and long range pulses in accordance with various embodiments of the present invention;

[0005] FIG. **3** shows measurement points in a field of view in accordance with various embodiments of the present invention;

[0006] FIG. **4** shows a flow diagram of methods in accordance with various embodiments of the present invention;

[0007] FIG. **5** shows a probability of not detecting an object as a function of distance in accordance with various embodiments of the present invention;

[0008] FIG. **6** shows a moving platform with an eye-safe LIDAR system in accordance with various embodiments of the present invention;

[0009] FIG. **7** shows a flow diagram of methods in accordance with various embodiments of the present invention;

[0010] FIGS. **8** and **9** shows a scanning light detection and ranging (LIDAR) system with a virtual protective housing and redundant detectors in accordance with various embodiments of the present invention;

[0011] FIG. **10** shows a side view of a transmit module in accordance with various embodiments of the present invention;

[0012] FIG. **11** shows a top view of a transmit module in accordance with various embodiments of the present invention;

[0013] FIG. **12** shows a side view of a receive module in accordance with various embodiments of the present invention;

[0014] FIG. **13** shows a top view of a receive module in accordance with various embodiments of the present invention;

[0015] FIG. **14** shows a cross sectional top view of an integrated photonics module in accordance with various embodiments of the present invention;

[0016] FIG. **15** shows a perspective view of the integrated photonics module of FIG. **14**;

[0017] FIG. **16** shows a scanning projector with an eye-safe LIDAR system in accordance with various embodiments of the present invention;

[0018] FIG. **17** shows an interactive display device in accordance with various embodiments of the present invention; and

[0019] FIG. **18** shows a short throw projector in accordance with various embodiments of the present invention.

DESCRIPTION OF EMBODIMENTS

[0020] In the following detailed description, reference is made to the accompanying drawings that show, by way of illustration, specific embodiments in which the invention may be practiced. These embodiments are described in sufficient detail to enable those skilled in the art to practice the invention. It is to be understood that the various embodiments of the invention, although different, are not necessarily mutually exclusive. For example, a particular feature, structure, or characteristic described herein in connection with one embodiment may be implemented within other embodiments without departing from the scope of the invention. In addition, it is to be understood that the location or arrangement of individual elements within each disclosed embodiment may be modified without departing from the scope of the invention. The following detailed description is, therefore, not to be taken in a limiting sense, and the scope of the present invention is defined only by the appended claims, appropriately interpreted, along with the full range of equivalents to which the claims are entitled. In the drawings, like numerals refer to the same or similar functionality throughout the several views.

[0021] FIG. **1** shows a scanning light detection and ranging (LIDAR) system with a virtual protective housing in accordance with various embodiments of the present invention. System **100** includes pulse generation circuit **190**, infrared (IR) laser light source **130**, scanning mirror assembly **114** with scanning mirror **116**, and mirror drive and control circuit **154**. System **100** also includes infrared (IR) detector **142**, time-of-flight (TOF) measurement circuit **144**, 3D point cloud storage circuit **146**, comparator **148**, and virtual protective housing circuit **180**.

[0022] Laser light source **130** may be a laser light source such as a laser diode or the like, capable of emitting a laser beam **162**. The beam **162** impinges on a scanning mirror assembly **114** which in some embodiments is part of a microelectromechanical system (MEMS) based scanner or the like, and reflects off of scanning mirror **116** to generate a controlled output beam **134**. In some embodiments, optical elements are included in the light path between light source **130** and mirror **116**. For example, system **100** may include collimating lenses, dichroic mirrors, or any other suitable optical elements.

[0023] A scanning mirror drive and control circuit **154** provides one or more drive signal(s) **155** to control the angular motion of scanning mirror **116** to cause output beam **134** to traverse a raster scan trajectory **140** in a field of view

128. In operation, light source **130** produces modulated light pulses in the nonvisible spectrum and scanning mirror **116** reflects the light pulses as beam **134** traverses raster scan trajectory **140**.

[0024] In some embodiments, raster scan trajectory **140** is formed by combining a sinusoidal component on the horizontal axis and a sawtooth component on the vertical axis. In these embodiments, controlled output beam **134** sweeps back and forth left-to-right in a sinusoidal pattern, and sweeps vertically (top-to-bottom) in a sawtooth pattern with the display blanked during flyback (bottom-to-top). FIG. **1** shows the sinusoidal pattern as the beam sweeps vertically top-to-bottom, but does not show the flyback from bottom-to-top. In other embodiments, the vertical sweep is controlled with a triangular wave such that there is no flyback. In still further embodiments, the vertical sweep is sinusoidal. The various embodiments of the present invention are not limited by the waveforms used to control the vertical and horizontal sweep or the resulting raster pattern. The vertical axis is also referred to as the slow scan axis, and the horizontal axis is also referred to as the fast-scan axis. The labels “vertical” and “horizontal” are somewhat arbitrary, since a 90 degree rotation of the apparatus will switch the horizontal and vertical axes. Accordingly, the terms “vertical” and “horizontal” are not meant to be limiting.

[0025] Although scanning mirror **116** is shown as a single mirror that scans in two dimensions, this is not a limitation of the present invention. For example, in some embodiments, mirror **116** is replaced by two mirrors, one scanning in one dimension, and a second scanning in a second dimension. Further, although system **100** is described having one or more MEMS devices to perform scanning of laser light pulses, this is not a limitation of the present invention. Any device or method for scanning light pulses along a scan path may be employed without departing from the scope of the present invention.

[0026] In some embodiments, scanning mirror **116** includes one or more sensors to detect the angular position or angular extents of the mirror deflection (in one or both dimensions). For example, in some embodiments, scanning mirror assembly **114** includes a piezoresistive sensor that delivers a voltage that is proportional to the deflection of the mirror on the fast-scan axis. Further, in some embodiments, scanning mirror assembly **114** includes an additional piezoresistive sensor that delivers a voltage that is proportional to the deflection of the mirror on the slow-scan axis. The mirror position information is provided back to mirror drive and control circuit **154** as one or more SYNC signals **115**. In these embodiments, mirror drive and control circuit **154** includes one or more feedback loops to modify the drive signals in response to the measured angular deflection of the mirror. In addition, in some embodiments, mirror drive and control circuit **154** includes one or more phase lock loop circuits that estimate the instantaneous angular position of the scanning mirror based on the SYNC signals.

[0027] Mirror drive and control circuit **154** may be implemented using functional circuits such as phase lock loops (PLLs), filters, adders, multipliers, registers, processors, memory, and the like. Accordingly, mirror drive and control circuit **154** may be implemented in hardware, software, or in any combination. For example, in some embodiments, control circuit **154** is implemented in an application specific integrated circuit (ASIC). Further, in some embodiments, some of the faster data path control is performed in an ASIC and overall control is software programmable.

[0028] IR detector **142** includes one or more photosensitive devices capable of detecting reflections of IR laser light pulses. For example, IR detector **142** may include one or more PIN photodiodes, Silicon photomultipliers (SiPM), avalanche photodiodes (APD), or the like. Each point in the field of view that is illuminated with an IR laser light pulse (referred to herein as a “measurement point”) may or may not reflect some amount of the incident light back to IR detector **142**. If IR detector **142** detects a reflection, IR detector **142** provides a signal **143** to TOF measurement circuit **144**.

[0029] TOF measurement circuit **144** measure times-of-flight (TOF) of IR laser light pulses to determine distances to objects in the field of view. In some embodiments, virtual protective housing circuit **180** provides a timing signal (not shown) corresponding to the emission time of a particular IR laser light pulse to TOF measurement circuit **144**, and TOF measurement circuit **144** measures the TOF of IR laser light pulses by determining the elapsed time between the emission of the pulse and reception of the reflection of the same pulse.

[0030] TOF measurement circuit **144** may be implemented using any suitable circuits. For example, in some embodiments, TOF measurement circuit **144** includes an analog integrator that is reset when the IR pulse is launched, and is stopped when the reflected pulse is received. TOF measurement circuit **144** may also include an analog-to-digital converter to convert the analog integrator output to a digital value that corresponds to the time-of-flight (TOF) of the IR laser pulse, which in turn corresponds to the distance between system **100** and the object in the field of view from which the light pulse was reflected.

[0031] 3D point cloud storage device **146** receives X,Y data from mirror drive and control circuit **154**, and receives distance (Z) data on node **145** from TOF measurement circuit **144**. A three-tuple (X,Y,Z) is written to 3D point cloud storage device for each detected reflection, resulting in a series of 3D points referred to herein as a “point cloud.” Not every X,Y measurement point in the field of view will necessarily have a corresponding Z measurement. Accordingly, the resulting point cloud may be sparse or may be dense. The amount of data included in the 3D point cloud is not a limitation of the present invention.

[0032] 3D point cloud storage device **146** may be implemented using any suitable circuit structure. For example, in some embodiments, 3D point cloud storage device **146** is implemented in a dual port memory device that can be written on one port and read on a second port. In other embodiments, 3D point cloud storage device **146** is implemented as data structures in a general purpose memory device. In still further embodiments, 3D point cloud storage device **146** is implemented in an application specific integrated circuit (ASIC).

[0033] Comparator **148** compares the distance data (Z) on node **145** to a threshold value on node **147**, and if the distance is less than the threshold, then comparator **148** asserts the short range object detection signal on node **184**. The short range object detection signal alerts VPH circuit **180** to the detection of an object within a “short range,” where “short range” is determined by the value of the threshold on node **147**. For example, if the threshold is set to a value corresponding to a distance of five meters, and the detected distance is lower than that threshold, then an object closer than five meters has been detected, and VPH circuit **180** will be notified by the short range object detection signal on node **184**.

[0034] The threshold value on node **147** and the corresponding short range distance may be modified by VPH circuit **184** based on any criteria. For example, the threshold may be a function of IR laser pulse power, pulse duration, pulse density, wavelength, scanner speed, desired laser safety classification, and the like. The manner in which the threshold value is determined is not a limitation of the present invention.

[0035] VPH circuit **180** operates to manage accessible emission levels in a manner that allows overall operation to remain eye-safe. For example, in some embodiments, VPH circuit **180** controls whether a "short range pulse" or "long range pulse" is generated by setting a pulse energy value on node **185**. The emitted pulse energy may be controlled by one or more of pulse power, pulse duration, or pulse count.

[0036] VPH circuit **180** may also control the timing of emitted pulses via the timing signal on node **157**. In some embodiments, for every measurement point in the field of view, VPH circuit **180** signals pulse generation circuit **190** to generate a short range pulse that can detect objects with a very high level of confidence out to a distance sufficient to provide a virtual protective housing. As used herein, the term "short range pulse" refers to a pulse that is considered eye-safe at a very short range. For example, in some embodiments, the energy levels of the short range IR laser light pulses may be maintained below the IEC 60825.1 Class 1 Accessible Emissions Limit, such that short range IR laser light pulses can be emitted at every measurement point without risking injury to a human eye.

[0037] If an object is detected within the short range distance, the corresponding three-tuple (x,y,z) may be written to the 3D point cloud storage device **146**, and system **100** provides a virtual protective housing by not emitting any higher energy pulses at that measurement point. If, however, a short range object is not detected, system **100** may emit one or more "long range pulses" that are of higher total energy to detect objects beyond the short range distance. For example, in some embodiments, system **100** may emit a short range IR laser light pulse that is considered eye-safe at a distance of 100 millimeters (mm) that has a 50% probability of detecting a 5% reflective target at 36 meters (m) in bright sunlight. This short range pulse may have a one in 10 billion probability of not detecting a 10% reflective target at a distance of 12 m. Also for example, system **100** may emit a long range pulse capable of detecting objects up to 200 m distant while remaining eye-safe beyond four meters distance. In this example, system **100** may emit short range pulses that have an extremely high probability of detecting objects within four meters, and then emit long range pulses that are capable of detecting objects at 200 m.

[0038] As used herein, the term "long range pulse" refers to one or more pulses with higher total energy than short range pulses. For example, in some embodiments, a single long range pulse may be emitted, and the single long range pulse may have higher energy than a single short range pulse, and in other embodiments, multiple long range pulses may be emitted, and the total energy of the multiple long range pulses may be higher than the single short range pulse.

[0039] Virtual protective housing circuit **180** may be implemented using any suitable circuit structures. For example, in some embodiments, VPH circuit **180** may include one or more finite state machines implemented using digital logic to respond to short range object detection and conditionally signal pulse generation circuit **190** to emit long range pulses. Further, in some embodiments, VPH circuit **180** may include a processor and memory to provide software programmability of short range pulse energy, long range pulse energy, threshold values and the like. The manner in which VPH circuit **180** is implemented is not a limitation of the present invention.

[0040] FIG. **2** shows short and long range pulses in accordance with various embodiments of the present invention. Short range pulse **210** and long range pulses **230** are examples of IR laser light pulses that may be emitted by a LIDAR system at each measurement point. For example, LIDAR system **100** may emit short range pulse **210** and then conditionally emit one or more of long range pulses **230** based on whether a short range object is detected. Pulse amplitude is shown on the vertical axis and time is shown on the horizontal axis of the plot in FIG. **2**. Short range pulse **210** is shown being emitted at a first time and a threshold is shown representing a second time. The difference between the first and second times represents the short range distance. For example, in some embodiments, the threshold is set at approximately 33 nanoseconds (ns) corresponding to a short range distance of substantially five meters. In some embodiments, short range pulse **210** has an energy level that is considered eye-safe at a very short distance. For example, short range pulse **210** may be eye-safe at 100 mm from the LIDAR system from which it is emitted.

[0041] In some embodiments, if a short range object is detected, the LIDAR system does not emit any long range pulses for that measurement point, and the detected distance is written to the 3D point cloud. On the other hand, if a short range object is not detected, one or more long range pulses **230** is emitted in a manner that maintains accessible emissions at an eye-safe level. For example, short range pulse **210** may have an energy level that provides a very high probability of detecting an object within the short range distance, and long range pulse **220** may have a total energy level that is eye-safe at the short range distance and beyond. Long range pulses can follow shortly after the threshold time if no short range object is detected. For example, long range pulse **220** may be emitted within 100 ns of the threshold time, or at 133 ns. The times corresponding to the threshold and emission of long range pulses may be different in various embodiments based on the desired short range distance and processing times, and are not a limitation of the present invention.

[0042] In some embodiments, a single long range pulse **220** is emitted, and in other embodiments a train of long range pulses **230** is emitted for each measurement point. The number of long range pulses emitted at a single measurement point is not a limitation of the present invention. For example, in some embodiments, a single long range pulse may be emitted, where the single long range pulse has a higher energy than the short range pulse. Also for example, in some embodiments, multiple long range pulses may be emitted, and each long range pulse may have an energy level that is the same as the short range pulse, but the total energy of the multiple long range pulses is greater than the energy of the short range pulse.

[0043] Any number of pulses at any energy level may be employed to define multiple ranges. For example, a short range may be defined by the energy of a single short range pulse. Also for example, a medium range may be defined by multiple pulses, each having the same energy as the short range pulse, and a long range may be defined by one or more long range pulses with the same or greater energy as the short range pulse.

[0044] In some embodiments, a short range pulse is emitted at every measurement point, and in other embodiments, short range pulses are not emitted at every measurement point. For example, a short range pulse may be emitted at a first measurement point, and if a short range object is not detected, then long range pulses may be emitted at one or more subsequent measurement point without first emitting a short range pulse. This is possible in some embodiments, in part, because measurement points may be defined sufficiently close to one another to enable a valid assumption that when no short range object occupies a measurement point, no short range object occupies some number of subsequent measurement points.

[0045] FIG. **3** shows measurement points in a field of view in accordance with various embodiments of the present invention. Measurement points **310** are points on raster scan trajectory **140** at which the LIDAR system measures distance. For example, in some embodiments, a LIDAR system such as LIDAR system **100** (FIG. **1**) emits a short range pulse at each measurement point **310** to detect if an object is within the short range distance and then conditionally emit one or more long range pulses as described above.

[0046] The term "measurement point" as used herein, is not meant to designate an infinitely small point in space, but rather a small and finite continuous section of raster scan trajectory **140**. For example, the controlled output beam **134** (FIG. **1**) traverses a finite section of raster scan trajectory **140** during the round trip transit times of a short range pulse and long range pulse at each measurement point. The measurement point area is also a function of laser spot size (initial size and divergence) at the distance where it encounters an object. Accordingly, the "measurement point" encompasses an area, albeit very small, and the size and location of the area may be a function of many factors.

[0047] FIG. **4** shows a flow diagram of methods in accordance with various embodiments of the present invention. In some embodiments, method **400**, or portions thereof, is performed by a LIDAR system, embodiments of which are shown in previous figures. In other embodiments, method **400** is performed by a series of circuits or an electronic system. Method **400** is not limited by the particular type of apparatus performing the method. The various actions in method **400** may be performed in the order presented, or may be performed in a different order. Further, in some embodiments, some actions listed in FIG. **4** are omitted from method **400**.

[0048] Method **400** is shown beginning with block **410** in which a short range pulse energy level is set and the short range pulse is emitted. In some embodiments, this corresponds to setting a pulse energy level to a value that will result in eye-safe operation at a particular distance from the LIDAR system. For example, in some embodiments, a short range pulse energy level may be set by virtual protective housing circuit **180** (FIG. **1**) such that accessible emissions result in eye-safe operations at 100 mm, and in other embodiments, the pulse energy level may be set such that accessible emissions result in eye-safe operations at a minimum distance greater than 100 mm.

[0049] If a short range object is detected at **420**, then a 3D point (X,Y,Z) may be written to a 3D point cloud storage device such as 3D storage device **146** (FIG. **1**). If a short range object is not detected, then one or more long range pulses may be transmitted at **440**. As described above, short range object detection may be accomplished by detecting a reflection of the short rang pulse, measuring the time-of-flight of the detected reflection, and comparing that time-of-flight to a threshold. The value of the threshold corresponding to the short range distance may be set to any suitable value.

[0050] At **430**, one or more long range pulses are emitted. If an object is detected at **440**, then a 3D point (X,Y,Z) may be written to a 3D point cloud storage device such as 3D storage device **146** (FIG. **1**) and processing continues at the next measurement point at **460**. If an object is not detected, then processing continues at the next measurement point at **460** without writing a 3D point to the point cloud storage device.

[0051] FIG. **5** shows a probability of not detecting an object as a function of distance in accordance with various embodiments of the present invention. Probability curve **510** is a typical curve that may shift left or right based on many parameters including pulse energy level, reflectivity of the object, ambient light, etc. For example, in extremely bright sunlight, a short range pulse that is eye-safe at 100 mm may have 10^{-10} probability of not detecting an object with a 20% reflectivity at 20 m. This results in an even lower probability of not detecting an object at closer distances, so in this same scenario, a long range pulse that is eye-safe at 5 m provides a very robust virtual protective housing.

[0052] In some embodiments, the threshold corresponding to the short range distance and the energy level of the long range pulse(s) are set to values that result in the short range distance and the minimum eye-safe distance of the long range pulse(s) being equal. In other embodiments, the threshold corresponding to the short range distance and the energy level of the long range pulse(s) are set to values that result in the short range distance being greater than minimum eye-safe distance of the long range pulse(s).

[0053] FIG. **6** shows a moving platform with an eye-safe LIDAR system in accordance with various embodiments of the present invention. Automobile **610** is a platform upon which an eye-safe LIDAR system **620** is mounted. In some embodiments, eye-safe LIDAR system **620** is implemented using LIDAR system **100** (FIG. **1**) or any of the LIDAR systems discussed further below.

[0054] In some embodiments, the energy of short range pulses is increased when the platform upon which the LIDAR system is mounted is in motion. For example, when automobile **610** has a velocity above a threshold, the energy of short range pulses may have a level that results in accessible emissions eye-safe level at a minimum distance above 100 mm. In some embodiments, the minimum distance at which the accessible emissions result in eye-safe level may be a meter or more. Also for example, the energy of short range pulses may be increased with increased platform velocity. In some embodiments, the energy of short range pulses may be gradually increased as the platform accelerates between 2.5 meters per second (m/s) and 25 m/s.

[0055] Increasing the energy level of short range pulses may result in increased probability of detecting objects within the short range and/or increasing the short range within which objects can be detected. FIG. **6** shows an increased short range as a result of increased short range pulse energy.

[0056] FIG. **7** shows a flow diagram of methods in accordance with various embodiments of the present invention. In some embodiments, method **410**, or portions thereof, is performed by a LIDAR system, embodiments of which are shown in previous figures. In other embodiments, method **410** is performed by a series of circuits or an electronic system. For example, method **410** may be performed by a virtual protective housing circuit. Method **410** is not limited by the particular type of apparatus performing the method. The various actions in method **410** may be performed in the order presented, or may be performed in a different order. Further, in some embodiments, some actions listed in FIG. **7** are omitted from method **410**.

[0057] Method **410** corresponds to block **410** of FIG. **4**. Method **410** is shown beginning with block **710** in which a default short range pulse energy level and a default time threshold are set. In some embodiments, the short range pulse energy level is set such that the accessible emissions are eye-safe at a short distance (e.g., 100 mm or less), and the time threshold is set to a value that provides a very low probability of not detecting an object (see FIG. **5**).

[0058] At **720**, if a velocity is faster than a threshold, processing continues at **740**, and if a velocity is not faster than a threshold, processing continues at **730**. In some embodiments, the velocity corresponds to the velocity of a moving platform upon which the LIDAR system is mounted. For example, if the LIDAR system is mounted on an automobile, the velocity corresponds to the speed of the automobile. In some embodiments, the LIDAR system receives velocity information from the automobile, and in other embodiments, the LIDAR system includes a velocity sensor and does not rely on an external source of velocity information.

[0059] At **740**, the short range pulse energy level and the time threshold corresponding to the short range distance are increased. In some embodiments, the short range pulse energy is increased to a level that results in accessible emissions that result in eye-safe levels at a minimum distance of one meter. In other embodiments, the short range pulse energy is increased to a level that results in accessible emissions that result in eye-safe levels at a minimum distance greater than or less than one meter. At **730**, the short range pulse is emitted.

[0060] FIGS. **8** and **9** show scanning light detection and ranging (LIDAR) systems with a virtual protective housing and redundant detectors in accordance with various embodiments of the present invention.

[0061] Referring to FIG. **8**, LIDAR system **800** includes all of the components of LIDAR system **100** (FIG. **1**), and also includes a second IR detector **842**, second TOF circuit **844**, second comparator **848**, and OR gate **880**. In operation, the additional circuits provide a redundant short range object detection capability, and OR gate **880** will signal the detection of a short range object if either circuit detects a short range object.

[0062] Redundant short range object detection provides an additional measure of safety. For example, if one or the IR detectors, TOF circuits, or comparators should fail, the redundancy will ensure continued safe operation.

[0063] In some embodiments, IR detector **142** and second IR detector **842** receive reflected light through different optical paths. For example, IR detector **142** may receive reflected light along a path shown at **135** and IR detector **835** may share an optical path with the emitted light pulses. In embodiments represented by FIG. **8**, emitted IR laser light at **162** is reflected by mirror **116** to produce light pulses along path **834**, and any reflected light along path **834** will also be reflected by mirror **116** and reach IR detector **842** along path **835**.

[0064] In some embodiments, both of the detection and TOF circuits operate to detect short range objects, and only one of the detection and TOF circuits operate to measure long range distance and/or write to the 3D cloud storage device. For example, in embodiments represented by FIG. **8**, times-of-flight measured by either TOF circuit **844** or TOF circuit **144** may be used to detect a short range object, but only times-of-flight measured by TOF circuit **144** are used to populate the 3D point cloud.

[0065] Referring now to FIG. **9**, LIDAR system **900** includes VPH circuit **184**, pulse generation circuit **190**, 3D point cloud storage device **146**, OR gate **880**, and control circuit **154**. LIDAR system **900** also includes transmit module **910**, receive module **930**, TOF and short range detection circuits **940**, and TOF and short range circuits **950**.

[0066] Each of TOF and short range detection circuits **940** and **950** include a TOF circuit and comparator. For example, TOF and short range detection circuits **940** may include TOF circuit **844** and comparator **848** (FIG. **8**), and TOF and short range detection circuits **950** may include TOF circuit **144** and comparator **148** (FIG. **8**).

[0067] Transmit module **910** includes an IR laser light source to produce a pulsed laser beam, collimating and focusing optics, and one or more scanning mirror assemblies to scan the pulsed laser beam in two dimensions in the field of view. Transmit module **910** also includes an IR laser light detector that shares an optical path with emitted IR laser light pulses. Example embodiments of transmit modules are described more fully below with reference to later figures.

[0068] Receive module **930** includes optical devices and one or more scanning mirror assemblies to scan in two dimensions to direct reflected light from the field of view to an included IR light detector. Example embodiments of receive modules are described more fully below with reference to later figures.

[0069] Control circuit **154** controls the movement of scanning mirrors within transmit module **910** as described above with reference to FIG. **1**. Control circuit **154** also controls the movement of scanning mirrors within receive module **930**. In operation, control circuit **140** receives mirror position feedback information (not shown) from transmit module **910**, and also receives mirror position feedback information (not shown) from receive module **930**. The mirror position feedback information is used to phase lock the operation of the mirrors. Control circuit **540** drives microelectromechanical (MEMS) assemblies with scanning mirrors within transmit module **910** with drive signal(s) **945** and also drives MEMS assemblies with scanning mirrors within receive module **930** with drive signal(s) **947** that cause the mirrors to move through angular extents of mirror deflection that define the size and location of field of view **128**. The synchronization of transmit and receive scanning allows the receive aperture to only accept photons from the portion of the field of view where the transmitted energy was transmitted. This results in significant ambient light noise immunity.

[0070] As shown in FIG. **9**, the two dimensional scanning is performed in a first dimension (vertical, fast scan direction) and a second dimension (horizontal, slow scan direction). The labels "vertical" and "horizontal" are somewhat arbitrary, since a 90 degree rotation of the apparatus will switch the horizontal and vertical axes. As an example, the fast and slow scan directions are shown in FIG. **9** having a 90 degree rotation as compared to those shown in FIGS. **1** and **8**.

[0071] FIG. **10** shows a side view and FIG. **11** shows a top view of a transmit module in accordance with various embodiments of the present invention. Transmit module **910** includes laser light source **1010**, beam shaping optical devices **1020**, received energy pickoff device **1060**, mirror **1062**, beam shaping device **1064**, IR detector **1066**, scanner **1028**, and exit optical devices **450**.

[0072] In some embodiments, laser light source **1010** sources nonvisible light such as infrared (IR) light. In these embodiments, IR detector **1066** detects the same wavelength of nonvisible light, as does an IR detector in receive module **930** (FIG. **9**). For example, in some embodiments, light source **1010** may include a laser diode that produces infrared light with a wavelength of substantially 905 nanometers (nm), and IR detector **1066** detects reflected light pulses with a wavelength of substantially 905 nm. Also for example, in some embodiments, light source **1010** may include a laser diode that produces infrared light with a wavelength of substantially 940 nanometers (nm), and IR detector **1066** detects reflected light pulses with a wavelength of substantially 940 nm. The wavelength of light is not a limitation of the present invention. Any wavelength, visible or nonvisible, may be used without departing from the scope of the present invention.

[0073] Laser light source **1010** may include any number or type of emitter suitable to produce a pulsed laser beam. For example, in some embodiments, laser light source **1010** includes multiple laser diodes shown in FIG. **11** at **1112**, **1114**, **1116**, and **1118**. The pulsed laser light produced by laser light source **1010** is combined, collimated, and focused by beam shaping optical devices **1020** to produce a pulsed laser beam. For example, optical devices **1022** may collimate the laser beams on the fast axis, polarization rotators **1023** and beam combiners **1020** may combine laser beams, and optical devices **1022** may form the pulsed laser beam into a fan on the slow axis. Beam sizes and divergence values are not necessarily uniform across the various embodiments of the present invention; some embodiments have higher values, and some embodiments have lower values.

[0074] Scanner **1028** receives the pulsed laser beam from optical devices **1020** and scans the pulsed beam in two dimensions. In embodiments represented by FIGS. **10** and **11**, scanner **1028** includes two separate scanning mirror assemblies **1030**, **1040**, each including a scanning mirror **1032**, **1042**, where each scanning mirror scans the beam in one dimension. For example, scanning mirror **1032** scans the pulsed beam in the fast scan direction, and scanning mirror **1042** scans the pulsed beam in the slow scan direction.

[0075] Although scanner **1028** is shown including two scanning mirror assemblies, where each scans in a separate dimension, this is not a limitation of the present invention. For example, in some embodiments, scanner **1028** is implemented using a single biaxial scanning mirror assembly that scans in two dimensions. In some embodiments, scanning devices uses electromagnetic actuation, achieved using a miniature assembly containing a MEMS die and small subassemblies of permanent magnets and an electrical interface, although the various embodiments are not limited in this respect.

[0076] Exit optical devices **1050** operate on the scanning pulsed laser beam as it leaves the transmit module. In some embodiments, exit optical devices **1050** perform field expansion. For example, scanning mirror assembly **1028** may scan through maximum angular extents of 20 degrees on the fast scan axis, and may scan through maximum angular extents of 40 degrees on the slow scan axis, and exit optical devices **1050** may expand the field of view to 30 degrees on the fast scan axis and 120 degrees on the slow scan axis. The relationship between scan angles of scanning mirrors and the amount of field expansion provided by exit optical devices **1050** is not a limitation of the present invention.

[0077] Received energy pickoff device **1060** deflects received light (shown as a dotted line) that shares the transmit optical path with the emitted light pulses (shown as a solid line). The deflected received light is then reflected by mirror **1062**, focused by optical device **1064**, and detected by IR detector **1066**. In some embodiments, pickoff device **1060** includes a "window" that transmits the pulsed beam produced by the IR laser light source, and a reflective outer portion to deflect received energy outside the window. In other embodiments, pickoff device **1060** is a partial reflector that transmits a portion of incident light and reflects the rest. For example, a reflector that transmits 90% of incident light and reflects 10% of incident light will provide the IR detector with 10% of the light reflected off an object in the field of view. In still further embodiments, pickoff device **1060** may incorporate a polarizing beam splitter that transmits the pulsed laser beam (at a first polarization), and picks off received light of a different polarization. This is effective, in part, due to the reflections being randomly polarized due to Lambertian reflection. In still further embodiments, the outgoing laser beam and received energy may be directed to different portions of the scanning mirrors, and pickoff device **1060** may be an offset mirror positioned to reflect one but not the other.

[0078] IR detector **1066** may be an example embodiment of IR detector **842** (FIG. **8**). For example, in some embodiments, transmit module **930** implements the transmit side (with redundant IR detector) of LIDAR system **800**.

[0079] FIG. **12** shows a side view and FIG. **13** shows a top view of a receive module in accordance with various embodiments of the present invention. Receive module **930** includes IR detector **1210**, fold mirrors **1212**, imaging optical devices **1220**, bandpass filter **1222**, scanner **1228**, and exit optical devices **1250**.

[0080] Scanning mirror assemblies **1230** and **1240** are similar or identical to scanning mirror assemblies **1030** and **1040**, and exit optical devices **1250** are similar or identical to exit optical devices **1050**. Bandpass filter **1222** passes the wavelength of light that is produced by laser light source **1010**, and blocks ambient light of other wavelengths. For example, in some embodiments, the laser light source produces light at 905 nm, and bandpass filter **1222** passes light at 905 nm.

[0081] Imaging optical devices **1220** image a portion of the field of view onto IR detector **1210** after reflection by fold mirrors **1212**. Because scanner **1228** is scanned synchronously with scanner **1028**, arrayed receiver **1210** always collects light from the measurement points illuminated by the scanned pulsed beam.

[0082] FIG. **14** shows a cross sectional top view of an integrated photonics module in accordance with various embodiments of the present invention. Integrated photonics module **1410** includes both transmit module **910** and receive module **930**. In some embodiments, a photonics module include transmit module **910**, and a receive module that does not include a separate scanning assembly. For example, a photonics module may implement the optical portions of LIDAR system **800** (FIG. **8**) which includes a scanner on the transmit side that shares an optical path with an IR detector, and includes a receiver side without a separate scanner.

[0083] FIG. **15** shows a perspective view of the integrated photonics module of FIG. **14**. Integrated photonics module **1410** is shown having a rectangular housing with transmit module **910** and receive module **930** placed side by side. In some embodiments, transmit module **910** and receive module **930** are placed one on top of the other. The relative orientation of transmit module **910** and receive module **930** is not a limitation of the present invention.

[0084] FIG. **16** shows a scanning projector with an eye-safe LIDAR system in accordance with various embodiments of the present invention. Scanning projector **1600** includes all of the components shown in FIG. **1** and also includes image processing component **1602**, power control circuit **1604**, and visible laser light source **1630**. In some embodiments, visible laser light source includes red, green, and blue laser light sources that are pulsed to create visible pixels that result in a viewable image in field of view **128**.

[0085] Power control circuit **1604** is responsive to VPH circuit **184** to reduce power of visible laser light pulses when objects are detected in the field of view. For example, if a short range object is detected, power control circuit **1604** may blank the visible laser light or reduce power levels such that accessible emissions are eye-safe at the distance of the detected object.

[0086] FIG. **17** shows an interactive display device in accordance with various embodiments of the present invention. Interactive display device **1700** includes scanning projector **1600**, which in turn includes laser light sources **1630**, **130** and IR detector **142**. In some embodiments, interactive display device displays visible content and a user may interact through gesture recognition.

[0087] FIG. **18** shows a short throw projector in accordance with various embodiments of the present invention. Short throw projector **1800** is positioned on a shelf **1810** and projecting into field of view **1880** onto a wall **1720**. Projector **1800** includes any virtual protective housing circuits described above.

[0088] Although the present invention has been described in conjunction with certain embodiments, it is to be understood that modifications and variations may be resorted to without departing from the scope of the invention as those skilled in the art readily understand. Such modifications and variations are considered to be within the scope of the invention and the appended claims.

What is claimed is:

1. An apparatus comprising:

a laser light source to produce infrared (IR) laser light pulses at multiple energy levels at times corresponding to depth measurement points in a field of view;

a scanning mirror assembly to scan the IR laser light pulses in the field of view;

a first IR light detector to detect reflections of the IR laser light pulses from within the field of view;

time-of-flight (TOF) circuitry responsive to the first IR light detector to measure distances to objects at the depth measurement points in the field of view; and

a virtual protective housing circuit that, for a plurality of depth measurement points, causes the laser light source to emit a first IR laser light pulse at a first pulse energy to detect an object within a short range, determines there is no object within the short range, and emits at least one second IR laser light pulse having a total second energy level to detect an object within a long range, wherein the first energy level is lower than the total second energy level.

2. The apparatus of claim **1** further comprising:

a second IR light detector; and

second TOF circuitry responsive to the second IR light detector.

3. The apparatus of claim **2** further comprising:

a first optical path between the scanning mirror assembly and the field of view; and

a second optical path between the field of view and the first IR light detector, wherein the second IR light detector is positioned to receive light from the field of view through the first optical path.

4. The apparatus of claim **1** wherein the apparatus is mounted on a moving platform.

5. The apparatus of claim **4** wherein the first pulse energy is increased when the moving platform has a velocity above a threshold.

6. The apparatus of claim **4** wherein the first pulse energy increases with increased platform velocity.

7. The apparatus of claim **1** further comprising at least one visible laser light source to emit visible laser light, wherein the virtual protective housing circuit includes circuitry to reduce a power level of the visible laser light in response to the TOF circuitry.

8. An apparatus comprising:

a first laser light source to emit IR laser light pulses at times corresponding to measurement points in a two-dimensional field of view;

a scanning mirror assembly to reflect the IR laser light pulses at the measurement points in the field of view,

a first time-of-flight (TOF) measurement circuit to produce depth data representing distances to objects at the measurement points in the field of view in response to received reflections of IR laser light pulses;

pulse generation circuitry to first produce a short range IR laser light pulse and then produce at least one long range IR laser light pulse for each measurement point, wherein the short range IR laser light pulse is lower energy than the at least one long range IR laser light pulse; and

a 3D point cloud storage device to store 3D depth map information.

9. The apparatus of claim **1** wherein a pulse energy of the short range IR laser light pulse is below an eye-safe threshold at a first distance, and a total energy of the at least one long range IR laser light pulse is below an eye-safe threshold at a second distance.

10. The apparatus of claim **9** wherein the apparatus is mounted on a moving platform.

11. The apparatus of claim **10** wherein the first distance is increased when the moving platform has a velocity above a threshold.

12. The apparatus of claim **10** wherein the first distance is increased based on the velocity of the moving platform.

13. The apparatus of claim **8** further comprising a second TOF measurement circuit, wherein the first and second TOF measurement circuits measure TOF of reflections received on different optical paths.

14. The apparatus of claim **8** wherein the pulse generation circuitry is configured to generate the at least one long range pulse when no object is detected by the short range pulse, and to not generate the at least one long range pulse when an object is detected by the short range pulse.

15. The apparatus of claim **8** further comprising:

at least one visible laser light source to emit visible laser light; and

circuitry to reduce a power level of the visible laser light in response to the first TOF measurement circuit.

16. A method comprising:

scanning IR laser light pulses across multiple measurement points in a field of view;

generating a short range IR laser light pulse at a time corresponding to a first measurement point in the field of view;

if a reflection of the short range IR laser light pulse is detected within a first time period, measuring a time-of-flight of the reflection, and storing the time-of-flight as depth data in a 3D point cloud storage device;

if a reflection of the short range IR laser light pulse is not detected within the first time period, generating at least one long range IR laser light pulse at a time still corresponding to the first measurement point within the field of view, and storing time-of-flight of any received reflection of the at least one long range IR laser light pulse as depth data in the 3D point cloud storage device.

17. The method of claim **16** wherein short range IR laser light pulse is lower energy than a total energy of the at least one long range IR laser light pulse.

18. The method of claim **17** wherein the short range IR laser light pulse is eye-safe at a first distance.

19. The method of claim **18** wherein the long range IR laser light pulse is eye-safe at a second distance, wherein the second distance is larger than the first distance.

20. The method of claim **16** further comprising increasing a power of the short range IR laser light pulse when the laser light pulses are emitted from a moving platform.

21. The method of claim **16** wherein the long range IR laser light pulse comprises a plurality of long range IR laser light pulses.

22. The method of claim **16** further comprising:

scanning visible laser light pulses to form an image in the field of view; and

reducing power of the visible laser light pulses when a reflection of the short range IR laser light pulse is detected within the first time period.

23. The method of claim **16** further comprising generating at lease one long range pulse at a time corresponding to a subsequent measurement point within the field of view without first generating a short range pulse at the subsequent measurement point if a reflection of the short range IR laser light pulse is not detected within the first time period.

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